The Finite Element Analysis of Magnetic Field of the Hybrid Excitation Linear Synchronous Motor with Permanent Magnet and Electric Excitation

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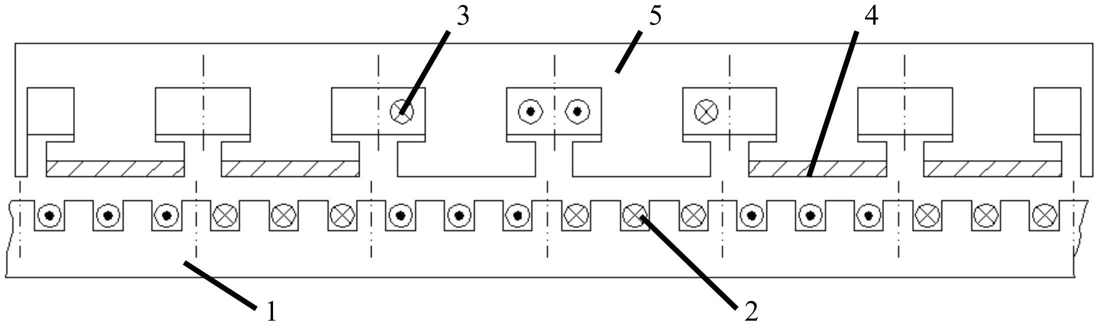
Abstract

This paper introduces the structure and characteristic of two novel kinds of hybrid excitation linear synchronous motor with permanent magnet and electric excitation—alternant hybrid excitation and even hybrid excitation linear synchronous motor. The air-gap magnetic field of them is analyzed with ANSYS8.1 software package. The results of the distribution of magnetic field and the electromagnetic propulsive force under the different exciting current are given. Then the advantage and disadvantage of the two kinds of excitation are compared. In the end, we compare the theoretical results with the experimental results of the actual models.

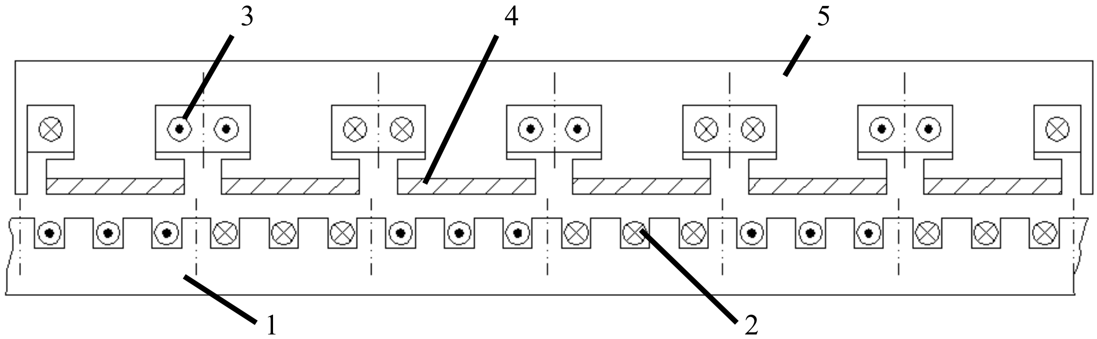
1 Introduction

When the brand, size and dosage of the permanent magnet of linear synchronous motor with permanent magnet excitation are chosen, its excitation system is as well as ascertained. So we can't adjust the intensity of excitation magnetic field according to actual need, which makes the application of the motor inconvenient. This is a problem. The hybrid excitation linear synchronous motor is brought forward to solve the problem. The so-called hybrid excitation linear synchronous motor means that in the secondary pole of linear synchronous motor, besides permanent magnet excitation, electric excitation winding generates magnetic flux also, both of them synthesizing in air-gap. While the amount of exciting current is adjusted, the intensity of air-gap magnetic field can be controlled.

The advantage of the hybrid excitation linear synchronous motor is that it is brushless, the intensity of magnetic field can be adjusted, and it is easy to control magnetic field. There are two kinds of structural design scheme. The first one is that excitation winding and permanent magnet are placed alternately (as shown in Fig.1-a). The second one is that there are both permanent magnet excitation and electric excitation in every secondary pole, both of which generate magnetic flux in the air-gap (as shown in Fig.1-b).



a) Alternant hybrid excitation



b) Even hybrid excitation

1. primary core 2. primary winding 3.secondary winding 4. permanent magnet 5. secondary core

Fig.1. Structure sketch map of two kinds of hybrid excitation

2 Finite element analysis

The suspension and propulsion are realized by air-gap magnetic field in the hybrid excitation linear synchronous motor with permanent magnet and electric excitation. So it is very important for analyzing the performance of motor to master the distribution of the air-gap magnetic field. To simplify the calculation, the magnetic circuit method (MCM) was mostly adopted to solve engineering problems in the past. MCM means that the existing uneven magnetic field is converted into equivalent multiple magnetic circuits, where magnetic flux is deemed as evenly distributing along every section and direction in each magnetic circuit. By that method, we can convert the calculation of magnetic field into the calculation of magnetic circuits. Then, by the introduction of some amendatory coefficients, the magnetic difference of potential of each equivalent magnetic circuit becomes the same as that of corresponding locations in magnetic field [2]. Although MCM is effective to deal with some general engineering design problems, it isn't so satisfactory when high precision is required, which calls for more precise method.

With the naissance of computer in the middle period of last century, the so-called finite element method (FEM) was brought forward for the highest precision and efficiency in the domains of computational mathematics, computational mechanics, and computational engineering. FEM is a method that converts the boundary value problem of partial differential equation into the discretization variational problem(i.e. functional extreme value problem) to obtain the numeric solution [4]. With FEM applied widely in many engineering domains, many kinds of FEM software package come out. Among those, ANSYS is a quite successful one, which includes one EMAG module having powerful function to analyze low frequency electromagnetic field. Thereinafter, we will apply ANSYS8.1 to analyze the distribution of air-gap magnetic field and the magnetic propulsive force of the hybrid excitation linear synchronous motor.

2.1 Analysis of the air-gap magnetic field

Because the motor has these characteristics as the transversal length of motor is far bigger than the length of air-gap, the primary winding is three phase mass winding, the end of winding is shorter, and all iron cores are lamination, it can be made for some simplified hypothesis as follows.

a. The distribution of magnetic field can be regarded as symmetrical in the axis direction. The current density vector $\vec{J}$ and the magnetic vector potential $\vec{A}$ have only the part of the axis direction, i.e. $J = J_z$, $A = A_z$.

b. The magnetic field outside the shell of motor can be ignored. Thus, the outward surfaces of the primary and secondary can approximately be regarded as an equivalent magnetic potential surface with zero vector value.

c. The distribution of current density in conductor is supposed to be symmetrical.

d. It can be assumed that the magnetic permeability of iron core is isotropic. At the same time the hysteresis effect and the eddy current effect are omitted.

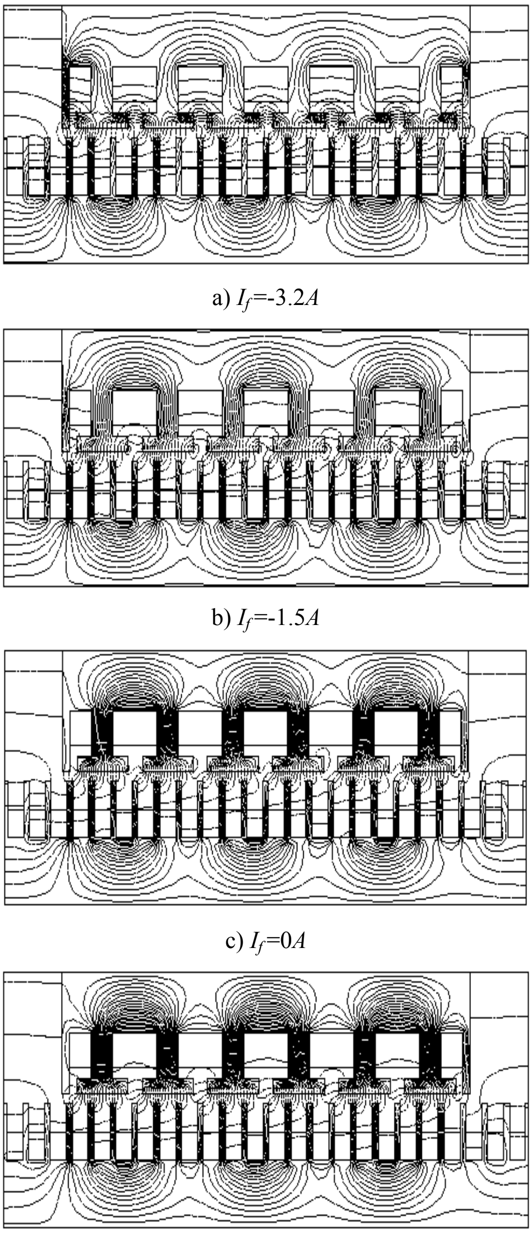
Based on the foregoing hypothesis, we adopt a two-dimension model to analyze the distribution of magnetic field. The parameters of model are shown in Table.1. They are also the parameters of prototype machine [5].

Overall length of primary	5520mm	Nominal voltage	380V
Primary pole span	45mm	Nominal current	3.8A
Length of air-gap	5mm	Nominal frequency	50Hz
Pitch of primary winding	45mm	Number of secondary pole	6
Type of primary winding	Three phase, Monolayer, Chain, Y connection	Length of secondary pole	35mm
Turn number of primary winding	163	Height of secondary pole	33mm
Wire diameter of primary winding	0.85mm	Height of secondary yoke	32mm
Equivalent height of primary slot	30.5mm	Turn number of secondary winding	395
Breadth of primary slot	11mm	Wire diameter of secondary winding	0.75mm
Breadth of primary tooth	4mm	Nominal exciting current of secondary winding	2.8A
Thickness of primary stack	50mm	Brand of permanent magnet	N35SH
Height of primary yoke	35mm	Size of permanent magnet	35mm×50mm×3mm

Table.1. Parameters of the hybrid excitation linear synchronous motor

The permanent magnet will be calculated as a current source. After the direction of charging magnetism, the relative permeability μ_r, and the coercive force H_c of permanent magnet are given in the motor model, ANSYS software will work out the equivalent surface current density.

Hereon, we analyze the model of motor when the secondary q axis superposes the phase a on the rated state. Then the triphase current value of the primary winding are respectively $i_a = \sqrt{2} I_N = \sqrt{2} \times 3.8 = 5.3740\ A$, $i_b = i_c = -\frac{\sqrt{2}}{2} I_N = -2.6870\ A$. When the secondary exciting current I_f is respectively -3.2/-1.5/0/1.5/3.2A, we analyze the two dimension distribution of magnetic field of the even hybrid excitation and alternant hybrid excitation linear synchronous motor with the method of static field analysis. The charts of magnetic lines of flux are shown in Fig.2 and Fig.3.



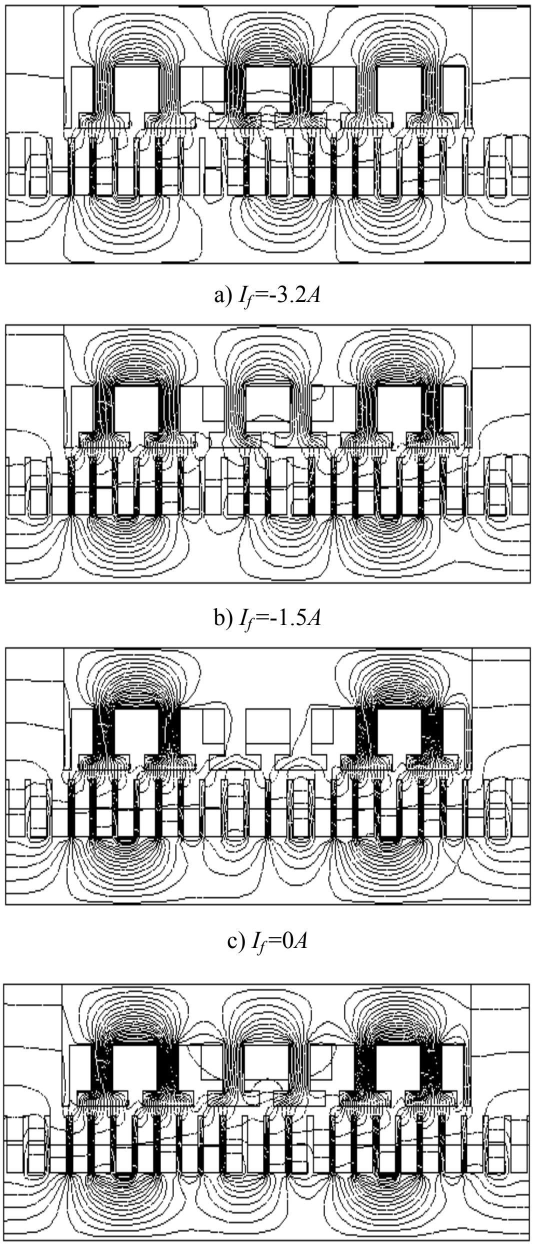
a) I_f=-3.2A

b) I_f=-1.5A

c) I_f=0A

d) I_f=1.5A

Fig.2. Charts of magnetic lines of flux of the even hybrid excitation linear synchronous motor under the different exciting current I_f



a) I_f=-3.2A

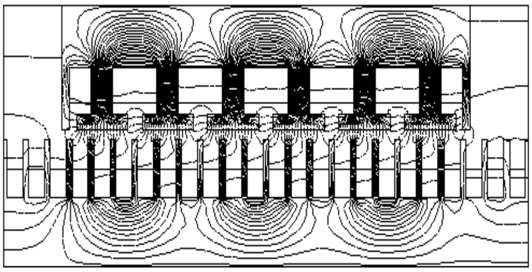
b) I_f=-1.5A

c) I_f=0A

d) I_f=1.5A

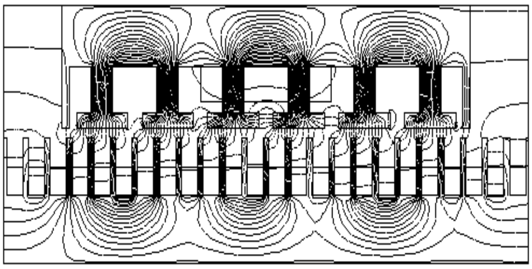
Fig.3. Charts of magnetic lines of flux of the alternant hybrid excitation linear synchronous motor under the different exciting current I_f

(Continued)



e) I_f=3.2A

Fig.2. Charts of magnetic lines of flux of the even hybrid excitation linear synchronous motor under the different exciting current I_f



e) I_f=3.2A

Fig.3. Charts of magnetic lines of flux of the alternant hybrid excitation linear synchronous motor under the different exciting current I_f

As shown in the above charts of magnetic lines of flux, the magnetic flux density of every couple poles of the even hybrid excitation linear synchronous motor boosts up gradually, with changing the exciting current from negative value to positive value. However the magnetic flux of electric excitation pole of the alternant hybrid excitation linear synchronous motor changes direction from being reverse to the magnetic flux direction of permanent magnet pole to being same to that, so the magnetic flux density of permanent magnet pole will vary from being weakened to being intensified. As shown in Fig.3, the magnetic flux density of electric excitation pole is approximatively equivalent in a) and e), likewise in b) and d), but the magnetic flux direction of them is contrary. In Fig.3-c), the magnetic flux density of electric excitation pole is almost zero. Comparing Fig.2 with Fig.3, it can be concluded that the even hybrid excitation linear synchronous motor has more symmetrical distribution of magnetic field than the alternant hybrid excitation linear synchronous motor. And the air-gap magnetic flux density of the former is higher than that of the latter under the same exciting current.

2.2 Analysis of electromagnetic propulsive force

The electromagnetic propulsive force is an important performance index of the hybrid excitation linear synchronous motor. In electromagnetic theory, there are two kinds of method to calculate electromagnetic force, i.e. the method of Maxwell's stress tensor and the method of virtual displacement [3].

2.2.1 Method of Maxwell's stress tensor

According to Maxwell's opinion, the volume force which acts on any area of a medium can be deduced to the tensile force acting on surface of the area. If the magnetic permeability of two kinds of medium are μ_a and μ_b, the force acting on object surface in the magnetic field is

$$F = \frac{\mu_b - \mu_a}{2\mu_a\mu_b}(B_n^2 + \mu_a\mu_b H_t^2) \tag{1}$$

The direction of force is from the medium with bigger magnetic permeability to the medium with smaller magnetic permeability. If two kinds of medium are respectively ferromagnetic material and air, the expression of the force is

$$F = \frac{\mu_r - 1}{2\mu_r\mu_0}(B_n^2 + \mu_r\mu_0 B_t H_t) \tag{2}$$

And the direction of force is always from ferromagnetic material to air.

2.2.2 Method of virtual displacement

It is a method to solve the electromagnetic force. Its theoretical basis is that the virtual displacement of the secondary begets the change of every unit of magnetic field. If the electromechanical coupling system is considered as a non-loss conservative system, magnetic power storage W_m is a state function of the conservative system, flux linkage Ψ and displacement x are independent variable of the system, then

$$W_m = \sum_1^n \int_0^{\Psi} i d\Psi = W_m(\Psi_1, \Psi_2, \cdots \Psi_n; x_1, x_2, \cdots x_m) \tag{3}$$

Supposed that in an interval *dt*, No. *k* of *n* coupled circuits takes place a virtual displacement dx_k, and the others are immobile, according to the conservation of energy principle, there is

$$dW_{\Omega} = dW_m + dW_e \tag{4}$$

In the above equation, dW_{W} and dW_e is respectively

$$dW_{\Omega} = F_k dx_k \tag{5}$$

$$dW_e = \sum_{i=1}^n i_i e_i dt = \sum_{i=1}^n i_i \frac{d\Psi_i}{dt} dt = \sum_{i=1}^n i_i d\Psi_i \tag{6}$$

According to equation (4), (5), and (6), it can be deduced that

$$dW_m = F_k dx_k - \sum_{i=1}^n i_i d\Psi_i \tag{7}$$

And from equation (3), can deduce that

$$dW_m = \frac{\partial W_m}{\partial x_k} dx_k + \sum_{i=1}^n \frac{\partial W_m}{\partial \Psi_i} d\Psi_i \tag{8}$$

Coupling equation (7) and (8), the force acting on the object in the magnetic filed is

$$F_k = \frac{\partial W_m(\Psi, x)}{\partial x_k} \tag{9}$$

ANSYS software package can automatically work out the electromagnetic propulsive force with above two kinds of method. Table.2 and Table.3 list the results of the electromagnetic propulsive force of two kinds of hybrid excitation linear synchronous motor under the different exciting current. Fig.4 is the graph of propulsive force and exciting current's relationship.

Exciting current I_f/A	Electromagnetic propulsive force F_1 (Method of virtual displacement)/N	Electromagnetic propulsive force F'_1 (Method of Maxwell's stress tensor)/N
-3.2	67.48	63.17
-2.5	84.45	79.43
-1.5	108.66	102.89
-0.5	132.55	126.36
0	144.15	137.90
0.5	155.38	149.14
1.5	176.66	170.68
2.5	194.73	189.11
3.2	203.78	197.95

Table.2. Values of propulsive force of even hybrid excitation linear synchronous motor

Exciting current I_f/A	Electromagnetic propulsive force F_1 (Method of virtual displacement)/N	Electromagnetic propulsive force F'_1 (Method of Maxwell's stress tensor)/N
-3.2	58.34	54.19
-2.5	66.58	62.39
-1.5	78.67	74.36
-0.5	90.84	86.34
0	96.90	92.29
0.5	102.96	98.22
1.5	115.13	110.07
2.5	127.23	121.78
3.2	135.51	129.75

Table.3. Values of propulsive force of alternant hybrid excitation linear synchronous motor

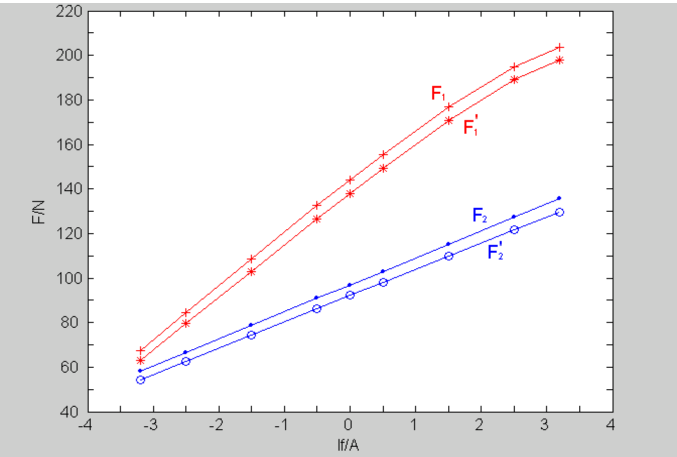


Fig.4. Comparison of calculated propulsive force of two kinds of hybrid excitation linear synchronous motor

As shown in the above graph, there is a fixed difference of propulsive force that is respectively worked out with two kinds of method. The electromagnetic propulsive force worked out with the method of virtual displacement is bigger than that with the method of Maxwell's stress tensor. It is related to the precision of partitioning model's mesh. After improving the partition precision, the difference of propulsive force will reduce.

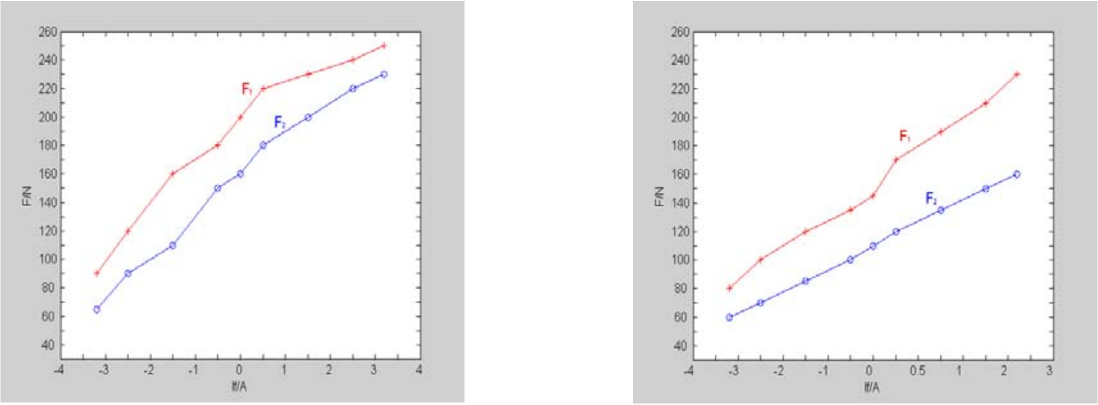
3 Experimental results of the prototype machine

An experimental prototype machine about 6-meters long has been made in the linear electric machine institute of Zhejiang University. In addition two secondary cars with even hybrid excitation and alternant hybrid excitation structure respectively have been made also. The prototype machine is consisted of 30 motors and divided into 3 segments for respectively current supplying. Its parameters are shown in Table.1. When the prototype machine is tested, we adopt the means of static force simulating dynamic force. Triphase symmetrical AC is conducted the primary winding. The traveling wave field of armature is moving with synchronous speed, while the exciting field is immobile. Therefore, a pull tension gauge fixed on the secondary car can measure the propulsive force [6].

In order to measuring the regulation function of exciting current to the air-gap magnetic field, we change the secondary exciting current I_f from negative value to positive value, and acquire a series of experimental data of propulsive force F on condition that primary power supply frequency f is respectively 5Hz, 25Hz, &50Hz (as shown in Table.4). In Table.4, the negative current value means that the magnetic flux generated by electric excitation counteract the one by permanent magnet, contrariwise the positive value means intensifying. F1 denotes the propulsive force of the car with even hybrid excitation structure, and F2 denotes the propulsive force of the car with alternant hybrid excitation structure. The graph of propulsive force and exciting current's relationship is Fig.5.

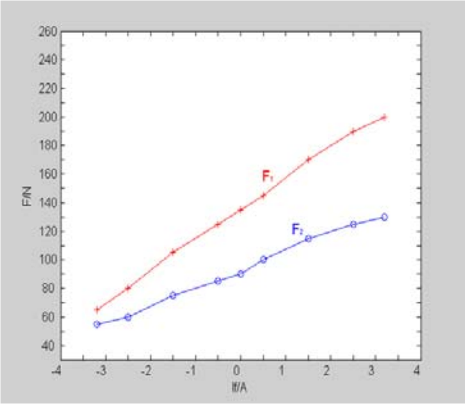
f	I_f/A	-3.2	-2.5	-1.5	-0.5	0	0.5	1.5	2.5	3.2
5Hz	F_1/N	90	120	160	180	200	220	230	240	250
	F_2/N	65	90	110	150	160	180	200	220	230
25Hz	F_1/N	80	100	120	135	145	170	190	210	230
	F_2/N	60	70	85	100	110	120	135	150	160
50Hz	F_1/N	65	80	105	125	135	145	170	190	200
	F_2/N	55	60	75	85	90	100	115	125	130

Table.4. Electromagnetic propulsive force F under the different exciting current I_f



a) f=5Hz

b) f=25Hz



c) f=50Hz

Fig.5. Comparison of experimental propulsive force of two kinds of hybrid excitation linear synchronous motor

4 Conclusion

On one hand the air-gap of prototype machine is asymmetric, on the other hand the precision of measuring apparatus is lower, so there is an error between the experimental outcome and the theoretical analysis outcome. But comparing the data in Table.2, Table.3, and Table.4, it can be deduced that the theoretical analysis outcome is approximately equivalent to the experimental outcome as primary power supply frequency being 50Hz. It's because the foregoing finite element analysis is on condition that the secondary q axis superposes the phase a on the rated state. This validates that the model and calculated outcome are accurate in the foregoing finite element analysis.

The advantage of alternant hybrid excitation is that the structure needs only to change the half structure of general permanent magnet linear synchronous motor, but the distribution of its magnetic field is asymmetric. When the even hybrid excitation linear synchronous motor is on stable operation, there is no current in the electric excitation winding, and only the magnetic field generated by permanent magnet provides the necessary electromagnetic propulsive force for motor running. The electric excitation winding offers adjustment to the air-gap magnetic flux. Only under some special circumstances such as starting, stopping, and sudden acceleration and deceleration, the current is conducted in electric excitation winding. According to the foregoing computer simulation analysis and experiment, it can be concluded that the even hybrid excitation linear synchronous motor has many advantages over the alternant hybrid excitation linear synchronous motor, such as more convenient adjustment to the air-gap magnetic field, more symmetrical distribution of the magnetic field, stronger propulsive force, and better performance.

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